Quantum mechanics, strong emergence and ontological non-reducibility

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We show that a new interpretation of quantum mechanics, in which the notion of event is defined without reference to measurement or observers, allows to construct a quantum general ontology based on systems, states and events. Unlike the Copenhagen interpretation, it does not resort to elements of a classical ontology. The quantum ontology in turn allows us to recognize that a typical behavior of quantum systems exhibits strong emergence and ontological non-reducibility. Such phenomena are not exceptional but natural, and are rooted in the basic mathematical structure of quantum mechanics.
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I. INTRODUCTION

There has been a recent proposal to solve the *problem of time* in background independent systems like general relativity (Gambini *et al.* 2009). In it, one has to take into account how quantum and gravitational effects influence the measurement of time. The latter ceases to be an ideal variable and becomes a physical variable subject to uncertainties of measurement and fluctuations of fundamental and inescapable nature (Frenkel 2010 and references therein; Ng and Van Dam 1993). The description of the evolution of quantum physical systems in terms of physical time changes the traditional Schrödinger picture (Gambini *et al.* 2007). Although the departures from the traditional theory are very small, they are enough —as we will argue later— to lead to an interpretation of quantum mechanics that solves the measurement problem in purely quantum terms. Such interpretation is known as the Montevideo interpretation (Gambini *et al.* 2011). A philosophical assessment of the interpretation was recently given by Butterfield (2014). In this paper we would like to argue that having at hand a realist interpretation of quantum mechanics allows to establish a general ontology of states and events that challenges some ontological prejudices inspired by classical systems that have clouded the understanding of the problem of emergence.

The organization of this paper is as follows. In section II we briefly review some notions of quantum mechanics. In Section III we review the measurement problem. Section IV introduces a new interpretation of quantum mechanics. In section V we discuss how to construct a new general ontology based on the new interpretation. Section VI discusses how emergence arises naturally from the new ontology. We end with a summary.

II. QUANTUM MECHANICS

Quantum physics has two fundamental properties from which very important consequences follow: it is quantum and it is probabilistic. First and foremost, it is quantum; the very name of this theory has to do with the fact that many fundamental quantities do not take continuous values, but certain preselected discrete values. For instance, in the quantum theory the orbits of the atom can only have certain values for the energy. To this fundamental property we owe the existence of matter organized in atoms, molecules and solid bodies. Every element or substance has a discrete set of behaviors that completely characterize it. Secondly, quantum physics is probabilistic. A complete knowledge of the state of a system will not allow us in most cases to know with certainty its future behavior. We have a great body of evidence indicating that the ignorance behind the probabilities is fundamental in nature (Schlosshauer *et al.* 2013). A more complete knowledge of the system is impossible: for instance, we just cannot predict when a given radioactive atom will emit a particle.

Many times there is the tendency to think that quantum phenomena are only relevant at microscopic scales and that classical physics is enough to describe phenomena at ordinary scales. Such belief is incorrect, quantum physics underlies many fundamental physical phenomena at ordinary scales: the stability of atomic and molecular structures, the very existence of solid matter and its electric, thermal, and optical properties, the origin of chemical reactions,

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the colors of certain substances are just some examples that rely crucially on quantum mechanics for their existence and explanation.

In spite of their relevance for macroscopic phenomena, the quantum processes underlying physics at ordinary scales are quite far from the ordinary experience. For instance in the well known double slit experiment, quantum systems like electrons neither behave like waves nor like particles. They have a dual behaviour. Each ordinary electron produces a dot on the screen as it a classical particle would, but when a large number of electrons have gone through the slits they reproduce the interference pattern of a wave. Even if the electrons go through the slits one by one they reproduce the wave pattern. One can say that the electron behaves as a particle when it is detected by the screen and as a wave when it travels undetected through the slits, interfering with itself. The double slit experiment allows us to introduce some concepts that will be useful in the forthcoming discussion of the measurement problem and the new interpretation of quantum mechanics. The behaviour of an electron in the photographic plate suggests that the electron has a certain *disposition* to produce an *event*, the appearance of dot in a given region of the plate with a given probability. This disposition for certain behaviors is determined by the wavefunction or *state* of the electron. While it propagates without being observed, the state given by the wavefunction obeys a wave equation: the Schrödinger equation. In quantum mechanics *measurements* are events to which we assign quantitative properties. For instance, in the double slit experiment, the position of the dot on the photographic plate.

III. THE MEASUREMENT PROBLEM

In order to explain the problem of measurement in quantum physics, let us come back to the previously mentioned double slit experiment. We have seen that electrons traversing one by one the double slit seem to interfere with themselves. One may wonder what happens if one illuminates one of the slits in order to determine whether the electron goes thorough that slit or the other. It happens that while the electrons are not illuminated as they travel from the source to the plate, they interfere with themselves and produce an interference pattern. The state of each electron may be described by a superposition corresponding to electrons going through both slits. When the electrons are illuminated when they pass through the slits, allowing to determine which of them they pass through, the state of the system suffers a sudden change and the electrons are forced to choose through which slit they will pass. What we observe in this case is the pattern produced by classical particles with two bright regions in front of each slit on the photographic plate. The state of the electron after being illuminated and before arriving to the plate is now given by a new kind of state known as statistical mixture. With certain probability, the electron is in a state localized in front of the upper slit and with the complementary probability will be in a state localized in front of the lower slit.

The passage from a superposition to a statistical mixture cannot be explained by the Schrödinger equation. Quantum mechanics therefore seems to require two different, incompatible, types of evolution: an evolution described by the Schrödinger equation and a different evolution that occurs when the system is measured, and an event is produced. But in a quantum Universe as the one we seem to live in, the measurement process should be analyzed entirely in quantum mechanical terms. What could distinguish a measurement from any other physical process to endow it with a different type of evolution?

The measurement problem can be summarized as follows: If one attempts to describe the measurement process using the usual evolution equation of quantum mechanics, that is the Schrödinger equation, one obtains that, after a measurement, the measuring device is left in a superposition in which the needle of its gauge is not pointing in a definite direction, but is generically pointing in all possible directions simultaneously. This result is not what happens when one performs an actual experiment; there the needle points to a definite position.

IV. A NEW REALIST INTERPRETATION OF QUANTUM MECHANICS

The founding fathers of quantum mechanics, Bohr and Heisenberg basically attempted to solve the measurement problem by denying the possibility of describing the world in pure quantum mechanical terms (Bohr 1995, Heisenberg 1958/2007). The basic problem with this proposal is that it needs to assume the existence of two different ontological realms: the classical —macroscopic— and the quantum —microscopic—, and the analysis of their interaction is outside the scope of any available theory. Moreover, in the last decade physicists have discovered in increasing numbers macroscopic systems whose description requires quantum mechanics, and many became convinced that the world has a fundamental quantum nature (Schlosshauer *et al.* 2013). Even Bohr used quantum mechanics for the description of the measuring device to address Einstein's objections (Bohr 1949). The closest thing we have to an explanation for the measurement process within the quantum theory is environmental decoherence (Schlosshauer 2010). It is based on the fact that when the state of a quantum system interacts with an environment with an

enormous number of (microscopic) degrees of freedom, the quantum system suffers transitions that almost look like the abrupt evolutions one needs to postulate in measurements.

Even if they are difficult to detect, quantum superpositions are still there and may be in principle observed. They simply are distributed in the environment and recovering them would require the observation of a system with a large number of degrees of freedom. Environmental decoherence is important because the measurement processes involves interactions with macroscopic systems with many degrees of freedom. Interactions with the environment were neglected for decades and the relevance of this effect was only recognized in the 1980's.

There is not universal agreement that decoherence solves the measurement problem. To begin with, as we just mentioned, quantum coherence is still there after an interaction with the environment and may be recovered. This is not what is supposed to happen in a measurement in quantum mechanics. Moreover, since the evolution of the system plus measuring device plus environment is unitary, there is no sense in which a measurement happens at some instant in time. And there is no objective criterion for when an event results from the measurement. Decoherence yields quantum states that resemble those of a system after a quantum collapse takes place, but there is no guide on what "resemble" means. Moreover there is no guide to say when the quantum state transitions from a superposition of coexisting possible outcomes to a set of exclusive outcomes with respective probabilities.

A new interpretation of quantum mechanics was recently proposed, called the Montevideo Interpretation (for a recent pedagogical review see Gambini and Pullin 2015). It is based on supplementing environmental decoherence with a more careful investigation of the measurement process, in particular taking into account the limitations of measurement that gravity imposes. It has the novelty of the inclusion in the quantum description of another factor up to now neglected. In the standard Schrödinger description of the evolution, time is treated as a classical external parameter, but time is actually measured by physical clocks that obey quantum mechanical laws. Quantum measurements of time have a limited precision. This limitation arises from quantum fluctuations and gravitational time delay effects (Frenkel 2010). One can show that a quantum mechanical treatment of time combined with fundamental limitations of measurements stemming from general relativity, leads to a modified Schrödinger evolution that allows transitions between quantum superpositions and statistical mixtures (Gambini *et al.* 2007) For a macroscopic object also subject to environmental decoherence this transitions may occur quite rapidly.

It is worthwhile remarking here that this interpretation results from a previous study and solution (Gambini *et al.* 2009) of the issue of time in quantum generally covariant theories. In these theories, like in any version of quantum gravity, the only well defined quantities are constants of the motion, in fact invariants under general coordinate transformations. It was shown that it is possible to describe the evolution using purely relational properties of quantum Dirac observables of which one of them plays the role of a clock.

When one takes into account the limitations in measurement imposed by quantum mechanics and gravity, the states that decoherence produces are indistinguishable from those produced by the measurement postulate. The "almost" of the standard approach to decoherence is removed by fundamental limitations of the theory itself and the transitions from superpositions to statistical mixtures required to explain measurements are a consequence of the theory. This in turn supplies an objective criterion that says when and what events may occur. Events occur when the state of a system resulting from a full quantum mechanical evolution becomes indistinguishable from a statistical mixture.

Events arise as random choices of the system when this criterion —the appearance of a statistical mixture— is fulfilled. It is important to remark that for quantum systems interacting with a macroscopic environment that has many degrees of freedom, events will be plentiful. They not only occur on measuring devices, they occur around us all the time. Measurements are nothing else but the assignment of quantitative properties to events occurring in measuring devices. In light of this new interpretation there is nothing mysterious or exceptional in the measurement process.

The philosopher of physics Jeremy Butterfield has recently assessed the significance of this interpretation, known as the Montevideo Interpretation and its analysis of time, and suggested that the resulting mechanism of decoherence is also compatible with a Many World interpretation (Butterfield 2014).

V. A QUANTUM ONTOLOGY

It is important to remark that having a realist interpretation of quantum mechanics not only allows us to understand the measurement process; it also allows understanding how a world with uniquely defined properties arises from a quantum mechanical world of potentialities[1] . This leads us to a new ontology based on quantum mechanics that we

[1] This not only applies to the Montevideo interpretation but may apply to other realist interpretations like the modal ones, although this has yet to be studied.

shall briefly discuss. A general quantum ontology addresses the question of which fundamental entities exist and their characteristics. Traditional ontologies are deeply ingrained in classical physics. For instance the concept of object as bundle of properties may sound plausible in classical physics but it is clearly superseded by quantum physics where, typically, systems do not have properties until events are produced.

To have a quantum theory with an interpretation is equivalent to knowing what beliefs about the world are allowed by the formalism. For this purpose, one relates the elements of the formalism with a consistent ontology. The interpretation here considered makes reference to primitive concepts like system, state, events and the properties that characterize them. Although these concepts are not new and are usually considered in quantum mechanics, one can assign them a univocal meaning only if one has an interpretation of the theory. For example, events could not be used as the basis of a realistic ontology without a general criterion for the production of events that is independent of measurements. Moreover, the concepts of state and system only acquire ontological value when the events also have acquired it.

Based on this ontology, objects and events can be considered the building blocks of reality. Objects will be represented in the quantum formalism by systems in certain states. In the new interpretation, events are the actual entities. On the other hand, states describe the potentialities or dispositions of the systems for the production of certain events. Concrete reality accessible to our senses is constituted by events localized in space-time. As Whitehead (Whitehead 1925/1997) recognized: "the event is the ultimate unit of natural occurrence."

Events come with associated properties. Events and properties in the quantum theory are represented by mathematical entities called projectors. Quantum mechanics provides probabilities for the occurrence of events and their properties. When an event happens, like in the case of the dot on the photographic plate in the double slit experiment, typically many properties are actualized. For instance, the dot may be darker on one side than the other, or may have one of many possible shapes.

Systems in a given state are what we colloquially call "objects". All hydrogen atoms are identical systems from the point of view of their potential behaviors, but their specific behavior at a given instant is determined by which state the atom is in. The quantum formalism associates to each system a Hilbert space, and to each state a vector or more generally a trace one positive definite self-adjoint operator. For instance the hydrogen atom system could be represented by the vector space of all its possible pure states. A basis from this space could be given by the standard orbitals associated with its stationary states. One could identify the hydrogen system with the element hydrogen. On the other hand, a particular hydrogen atom is a hydrogen system in a given state, it is an example of what we call an individual object and it has a precise disposition to produce events.

Notice that this quantum ontology has deep differences with the kind of ontologies that are usually considered in the discussion of the issue of emergence. For instance as noticed by McLaughlin, Brian and Bennett, Karen, "Supervenience", The Stanford Encyclopedia of Philosophy (Winter 2011 Edition), Edward N. Zalta (ed.) "Supervenience is a central notion in analytic philosophy. It has been invoked in almost every corner of the field. For example, it has been claimed that aesthetic, moral, and mental properties supervene upon physical properties. It has also been claimed that modal truths supervene on non-modal ones, and that general truths supervene on particular truths. Further, supervenience has been used to distinguish various kinds of internalism and externalism, and to test claims of reducibility and conceptual analysis." In the same article supervenience is defined in the following manner: A set of properties A supervenes upon another set B just in case no two things can differ with respect to A-properties without also differing with respect to their B-properties. In slogan form, "there cannot be an A-difference without a B-difference". As we shall see in the forthcoming sections this definition is particularly ill suited for the quantum description of the world where a system may not even have any property. Properties typically belong to events. Some properties may be ascribed to states only in some very specific situations.

VI. EMERGENCE

Emergent phenomena are said to arise out of and be sustained by more basic phenomena, while at the same time exerting a "top-down" control, constraint, or some other sort of influence upon those very sustaining processes. We are considering here the most stringent conception of emergence, which Mark Bedau (2003) calls strong emergence which assumes ontological novelty and "irreducible causal powers". He considers that "All the evidence today suggests that strong emergence is scientifically irrelevant... There is no evidence that strong emergence plays any role in contemporary science. The scientific irrelevance of strong emergence is easy to understand, given that strong emergent causal powers must be brute natural phenomena. Even if there were such causal powers, they could at best play a primitive role in science. Strong emergence starts where scientific explanation ends." This position is not exceptional but rather the rule among many contemporary philosophers.

In our view, efforts to explain this type of emergence have failed mainly because they assume implicitly an ontology inspired in classical physics. We will show in this paper that certain quantum mechanical systems present precisely

this kind of top-down control. We will attempt to show that quantum mechanical systems have ontologically new properties and downward causation where macro systems have effects on their micro components.

A. Ontologically new properties

Let us start by showing that quantum systems may have ontologically new properties. This has already been noted by Howard (2007), whom however, lacking an interpretation of quantum mechanics can only recover partially the results we obtain. In particular, here we can discuss the properties of a quantum object, whereas in his case the emergent properties are only about measurements, and downward causation is not discussed.

Quantum systems may be in certain quantum states, called entangled, that have well defined properties that neither follow from the properties of parts, nor from relations among them. To understand this statement better let us review how entangled states are defined and contrast them with systems in classical states. In classical physics the state of a system of particles is simply the union of the states of each of the particles given by their positions and velocities at a given instant. Its knowledge determine all the properties of the system. For instance the energy. All the properties of a classical system are functions of the properties of its components. In quantum mechanics things are very different. Most of the properties of a system do not have well defined values until measured; for instance the position of an electron in the double slit experiment is not well defined until a dot is produced in the photographic plate and it is detected.

In spite of the fact that in general one cannot attribute properties to states, quantum systems in a pure state have some well defined properties. In order to exemplify this, let us consider a spinning particle like the electron. While a classical particle rotating along an internal axis may have a continuum of values for the projection of its angular momentum on a given direction of space, in quantum mechanics its projections along an arbitrary axis are quantized. For instance, a spinning particle like the electron can only take two possible values of its projection along an axis z: up or down. Given a spinning particle like the electron one can measure its spin projection along z by using a Stern Gerlach device. It mainly consist in a magnet with S-N poles oriented along the axis in question, z in this case, and a photographic plate.

When one performs repeated measurements on a particles in a generic state one observes dots appearing in the upper region with certain probability an in the lower with the complementary probability. When the electron is in a state that leads with certainty to a dot in the upper region, one may say that it is in the state $|zup\rangle$. In this case one may assign the property "z up" to the state. This is the only property that one can assign to this state. The measurement of any other projection of the spin along a different direction will not lead to a unique value: i.e. always up or always down. *It is only when one knows with certainty what will be the behavior of the system in certain state that one may assign a property to the state.* Recall that while events always have many properties, and are completely characterized by them, one can only assign a property to a state if one knows with certainty to which event it will lead in certain measurement. Systems composed of several particles may also have states with some properties with well defined values. However, these properties may refer to the system as a whole and, in these systems, there may not be any property for the states of individual particles with well defined values. These composite systems are examples of what is known as systems in entangled states.

More in general, systems in entangled states are those that have properties with well defined values than cannot be inferred from those of their constituent parts. As we mentioned, and will show in the following example, it might even be the case that the states of the constituent parts have no well defined properties and yet the state of the whole system does.

Consider two electrons with spin in the z direction in a state

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}|1, z, \mathrm{up}\rangle|2, z, \mathrm{down}\rangle + \frac{1}{\sqrt{2}}|1, z, \mathrm{down}\rangle|2, z, \mathrm{up}\rangle. \tag{1}$$

This would represent a superposition of two electrons in different positions 1 and 2 with opposite spins. Neither the state of particle 1 nor the one of particle 2 have well defined properties. No matter what projection of the spin one measures, one has a probability one half of measuring up and one half of obtaining down. Even though each of the entangled electron do not have well defined properties for their spin components, the total system does. For instance, one can show that it has total spin $s = 1$ in Planck units, and z component of the total spin $s_z = 0$. It is only when the observations made on particle 1 and 2 are compared that one can discover the properties of the total system. One could also determine these properties if the complete system is measured. The constituents therefore now form an inseparable unit whose state is endowed with properties without the states of the individual particles having any property —any spin component— with well defined value. Notice that we made no statement about where the spinning particles are located in space.

This holistic behavior is actually not an exception but is the generic behavior of two quantum systems after an interaction. For instance, the precise vibrational modes of a molecule depend on the entangled system of electrons and nuclei. The emergent properties of such systems are crucial for explaining (at least some) chemical or biological properties in terms of physics. For instance, the vibrational modes of molecules are key to explaining why water is transparent. Ontological novelty manifests itself in the emergence of new properties that do not result from properties of the parts. They arise only when the composite structure is constituted. The philosopher of science Paul Teller (1986) was the first in noticing that quantum phenomena show relations that do not stem from non-relational properties of their relata, as is characteristic of the classical description of the world. However, the ontological meaning of his observation could not be elucidated because he could not discard a purely instrumentalist interpretation and his use of the notion of property is still reminiscent of classical physics. Entangled systems present what Teller calls: relational holism.

B. Downward causation

A strong form of emergence also requires downward causation, namely, the emergence of novel causal properties. Here a double goal arises: to characterize such form of causality in physical terms and to show that at least certain quantum systems, exhibit downward causation. A notion of causality that is suitable to the ontology of states and events has been developed by Chakravartty (2007). He says "So what does it mean to say that causal properties 'do the work' of causation?.... a causal property is one that confers dispositions on the objects that have them to behave in certain ways when in the presence or absence of other objects with causal properties of their own." This dispositional idea of causality is the one we have adopted in this work: recall that quantum states characterize dispositions to produce events. A system will present downward causation if the parts have some behaviors that are dictated by the state of the whole and that cannot be predicted from the knowledge of the state of the parts. The previous example of an entangled state shows that in quantum mechanics there is state non-separability. The states of the parts are just a statistical mixture of up components and down components while the complete entangled state has more information. It is this state non-separability that leads to downward causation. Let us study this behavior in some detail.

Let us assume George prepares the entangled state we discussed before and sends particle 1 to Alice and particle 2 to Bob. We will assume they both have devices that allow them to measure projections of spin along x or y. Without any communication, Alice and Bob choose independently and in a random fashion to measure one of these projections every time they receive a particle. As we mentioned, if the system is in this state it does not matter which component they measure, they will have 50% probability of measuring "up" and 50% "down". However, if they compare notes, they would realize that the sequences will be correlated: whenever they happened to measure the spin in the same direction their results were opposite, up for Alice and down for Bob or vice versa. They could never have figured that out by looking at the individual systems in isolation The complete system has a certain non locality such that when one electron chose to answer "up", the other necessarily needs to chose "down". Such correlation does not involve time, it is instantaneous.

There is a theorem, known as Bell's theorem (Mermin 1985), that establishes that it is not possible to explain this kind of behavior assuming that each part follows a pre-established set of instructions, in other words, assuming that each part has some local hidden information telling it how to act before each measurement. Certain behaviors of portions of a quantum system cannot be explained in terms of the states of its components. To put it differently, the state of the total system is not mathematically determined by the states of its components. Since we have characterized the causal power of a system by its disposition to produce certain effects, downward causation will be related to the non-separability of the quantum state of a whole and the dispositions it induces on its components to produce events.

C. A chemical example

Let us consider a specific example relevant to chemistry: the emergence of a molecule via the chemical bonding of its atomic components. Let us take a simple molecule of ionic hydrogen, formed by two atoms of hydrogen and stripping them of one electron. One can actually show rather straightforwardly that a hydrogen atom and a proton will tend to form a molecule. Using quantum mechanics one computes the minimum energy that the system has when the electron orbits around one of the protons and the minimum energy when it orbits around both. It turns out that the latter is lower than the former (Cohen-Tannoudji et al. (1978). As a consequence, after the molecule is formed one would have to add energy (or apply a force) to separate it. A chemical bond is therefore formed. This would be an example of how the molecular structure of matter can be explained in terms of quantum mechanics. Different molecules will require different studies, but in all cases the bonded configuration will be the one with the lowest energy. In complex

molecules there can be several configurations that correspond to local minima of the energy function and all of them will be possible states of the molecule. Chemically, the bonds can originate in different mechanisms depending on the molecule in question, but they can all be explained in physical terms.

Ontologically this example shows how molecular structures emerge from atomic ones. Chemical compounds arise as emergent phenomena of quantum states where the subsystems lose individuality. Epistemologically the example illustrates how some chemical concepts can be reexpressed in physical terms. The quantum state of the molecule consisting of two protons and an electron is an entangled state of the three particles. Quite a few of the behaviors of the molecule can only be explained with a state for the complete system, which cannot be described just in terms of states of the parts. An example is given by the vibrational modes associated with the oscillation of the protons around their equilibrium positions. These have very real consequences: they influence the ability of the molecule to emit or absorb light of certain frequencies. The emission or absorption is directly related with a rearrangement of the protons and electrons that are a manifestation of the downward causation of the complete system on its component parts. If one tried to describe that behaviour only in terms of the component states, lets say of the electrons assuming fixed positions of the protons, one could not reproduce the observed spectral lines, which are studied with great precision experimentally. Entanglement in quantum chemistry has actually been extensively analyzed, see for instance Huang, Wang and Kais (2006) and references therein.

Entanglement is about correlations. In quantum chemistry calculations, the correlation energy is defined as the energy error of the Hartree-Fock approximation to the wavefunctions. Electron correlations are important in many atomic, molecular and solid state properties.

Summarizing, in the language of the new ontology, for the above example the *object* is the system composed of the two protons and the electron in one of the system's possible states. An *event* corresponds to the observation of a photon of a certain frequency when it traverses a medium composed by the above objects. *Downward causation* occurs because one needs to consider the complete entangled system to predict precisely the vibrational modes and from them the optical behavior of the system (for instance absorption lines).

VII. CONCLUSIONS

Summarizing, by introducing in the analysis the use of quantum physical clocks for the description of the evolution, one can show that the standard Schrödinger equation needs to be slightly modified. In certain conditions as the ones present in measuring devices one can show that quantum superpositions may evolve into statistical mixtures. This provides an objective criterion that says when and what events may occur. In terms of the notions of this new realistic interpretation one can define a quantum ontology that leads to a revision of the notion of matter and its potentialities. This allows us to notice that systems of particles in entangled states have new capabilities and emergent properties. The simplistic notion of hierarchical systems with progressive complexity in which one goes from subatomic particles to atoms to molecules or from cells to tissues, organs, and living organisms, is inadequate. The quantum theory implies that the lower levels are modified even up to the point where they lose part of their individuality when they integrate into an entangled system in a higher level of the hierarchy. The emergent structure has novel properties and downward causation.

The present analysis may be considered as epistemologically reductionist because it allows to explain the appearance of novel properties and downward causation in purely physical terms. However ontologically it shows how different levels of reality may present emergent new properties and states with top down causation. In that sense, organization in higher level wholes are significant and the efficacy of the higher levels undeniable: one has ontological non-reducibility.

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